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LONGITUDINAL MOMENTUM MINING OF ANTIPROTONS AT THE FERMILAB RECYCLER: PAST, PRESENT AND FUTURE*

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Abstract

The technique of longitudinal momentum mining (LMM)[1] in the Fermilab Recycler was adopted in early 2005 to extract thirty-six equal intensity and equal 6D-emittance antiproton bunches for proton-antiproton collider operation in the Tevatron. Since that time, several improvements have been made in the Recycler and the mining technique to handle higher intensity beams. Consequently, the Recycler has become a key contributor to the increased luminosity performance observed during Tevatron Run IIb. In this paper, we present an overview of the improvements and the current status of the momentum mining technique.

INTRODUCTION

The success of the Fermilab collider program depends significantly on maximizing the integrated luminosity delivered to the experiments, as detailed in the Run IIb upgrade plans [2]. To this end, the Recycler [3] became the primary antiproton repository for the collider.

The Recycler is a permanent magnet 8 GeV storage ring equipped with both stochastic [4] and electron cooling [5] systems to reduce the antiproton beam emittances. The stored antiproton beam intensity in the Recycler has been steadily increased over the past few years to a current maximum of 450 $\times10^{10}$, with an eventual goal of 600 $\times10^{10}$.

Since early 2005, we have used the LMM technique to extract antiproton bunches from the Recycler for the Tevatron shots. The primary goal of this technique is to transfer thirty-six antiproton bunches of equal intensity and equal emittance (transverse and longitudinal) to the Tevatron from the dense region of the cold antiproton stack and leave the remaining portion of the beam in the Recycler for future use. The longitudinal emittance of the beam in the Recycler is cooled to approximately 60 eV s before mining, irrespective of the stack size. This allows for efficient use of the stored antiprotons in the collider operation and called for several improvements in the Recycler to handle higher intensity beams. In this paper, we give an overview of the various upgrades which led to the current performance of the Recycler.

IMPROVEMENTS IN THE RECYCLER

There are a number of upgrades in the Recycler that helped LMM. These include: 1) implementation of electron cooling (e-cooling) in addition to stochastic cooling, 2) improvements in the Recycler LLRF system to minimize the emittance dilution during antiproton stacking and extraction, 3) soft mining and 4) change in transverse tune operating points. As the density of antiprotons is increased, transverse beam instability is observed. To eliminate this problem a transverse damper operating in a frequency range between nearly DC to 30 MHz was added [6] to the Recycler.

Stochastic Cooling and the e-cooling

At Fermilab, antiprotons are produced by bombarding an inconel-600 target with 120 GeV protons. The antiprotons are initially stored in the Fermilab Accumulator Ring and cooled in all six dimensions using stochastic cooling. Subsequently, the beam is transferred to the Recycler barrier buckets whenever the stack size in the Accumulator Ring reaches between 40-60$\times10^{10}$. The transverse and longitudinal emittance of the antiprotons at the time of injection to the Recycler is 6-10 π mm-mr and 12 eV s per injection, respectively; significant emittance dilution occurs during the injection process.

The antiprotons in the Recycler are cooled using two different techniques. Stochastic cooling reduces the transverse emittance to 2 π mm-mr in about 2 hours with a very small amount of longitudinal cooling. e-cooling complements the stochastic cooling system by cooling the longitudinal emittance from about 120 eV s to 60 eV s in <30 mins [7] (this is the fastest cooling seen so far). With e-cooling the antiproton mining efficiency went up from <75% to >95%. The e-cooling in the Recycler is first of this kind.

Figure 1 shows the RF waveforms and wall current monitor data taken before (Fig 1a) and after (Fig. 1b) LMM on about 300 $\times10^{10}$ antiprotons just prior to preparing each of the nine batches for extraction to the Tevatron; different stages of improvements are also shown in Fig. 1.

Recycler LLRF

The Recycler LLRF is a VXI based system [8] with an embedded controller and several Fermilab-developed size C VXI modules. The Fermilab modules contain a 32-bit floating point SHARC™ DSP for local high-speed processing and intermodule data exchange. The primary functionality of the LLRF system is to provide 8 independent RF barrier waveforms. An 8-channel arbitrary waveform generator (ARB) may play one of 15 stored waveforms, each containing 256 8-bit signed integers, on each channel. Prior to output, each channel is multiplied by an independently adjustable gain and the

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channel outputs summed. The eight ARB channels are clocked independently using the outputs from three Direct Digital Synthesizer (DDS) modules running at harmonic 588 of the Recycler revolution frequency—89,811.2 Hz. The phase for each DDS channel can be set independently allowing accurate control of position for each ARB waveform within the Recycler ring. The system also contains a mode 0 damper and a 4-channel digitizing oscilloscope.

Recent software upgrades to the LLRF system support waveform morphing operations. During the morphing procedure, new ARB waveforms are calculated on the embedded controller, downloaded and played on a single ARB channel at a 60 Hz rate. Morphing capabilities have been used to merge injected antiproton beams into the stored beam region and to prepare a set of four antiproton bunches for injection into the Tevatron. In both cases, reduced emittance dilution was observed.

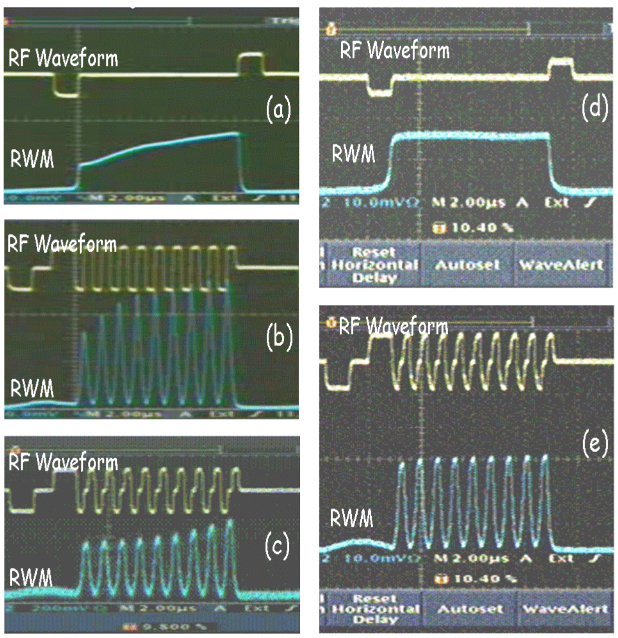

Figure 1: RF waveform and the wall-current monitor data in the Recycler (a) before mining without adaptive feed-forward corrections, (b) LMM with hard mini-barrier buckets, (c) LMM with soft mini-barrier buckets. Unequal intensity bunches were seen in both cases. With adaptive feed-forward corrections (d) before LMM, (e) after LMM with soft mini-barrier buckets. Equal intensity and equal emittance bunches are formed in this case.

Additional hardware/software upgrades to the system involved integrating a VME digitizer containing an FPGA processor [9]. The digitizer accepts the ARB output (LLRF drive) and HLRF fanback signal as inputs. Errors in the HLRF fanback due to non-linearities in the cavity power amplifiers produce an asymmetric barrier bucket and a slope in the potential well holding the antiprotons, as shown in Fig 1(a). The errors between the HLRF fanback and LLRF drive are measured and a correction calculated by the FPGA for output. This digitizer output is then summed with the LLRF drive to idealize the voltage played out on the HLRF cavities.

Figure 1(a) shows the line charge distribution (RWM) of the antiprotons in a 6.1 μs-long rectangular barrier bucket prior to the application of adaptive feed-forward correction described above. The asymmetry in RWM shown in Fig. 1(a) has been observed for stack sizes greater 100 $\times 10^{10}$ antiprotons and longitudinal emittance ~60 eV s, and is found to increase with stack intensity (and inversely to square of RMS energy spread of the stack [9]). LLM on similar asymmetric distributions led to over 200% bunch-by-bunch intensity variation in the Tevatron. RWM data for the antiproton beam with the adaptive feed-forward corrections applied is shown in Fig. 1(d).

Soft Mining

As the antiproton stack size in the Recycler increased, the peak density of mined bunches increased significantly (see Fig. 1(b)). Changing the mining RF waveform from "hard" to "soft" (Fig. 1(c)) reduced the peak density by approximately 35%. This helped to keep the Recycler beam farther from resistive wall instability during mining. The soft-mining is also expected to help LMM at higher stack sizes than those currently in use.

Change in Transverse Tune Operating Points

Prior to mid-2006, there was an issue related to the bunch-by-bunch transverse emittance variation (~300%) in the Tevatron at collision. This variation originated during the mined state of the antiprotons just before transfer to the Tevatron. In addition, the lifetime of the beam in the Recycler typically fell from several hundred hours to about a hundred hours during the mined condition. The conjecture was that the main culprit for such behavior was the transverse tunes of the Recycler, (Q_H=0.414, Q_V=0.422) which were driving the antiproton single-particle resonance.

We changed the Recycler tune operating point to (Q_H=0.456, Q_V=0.465) [10] where neither electron beam-antiproton instability nor the single-particle resonance seems to be a problem. This significantly improved the LMM for all antiproton stack sizes. Further, the bunch-by-bunch transverse emittance variation got reduced to <10% in the Tevatron. This also provided significantly wider favorable tune space for operation.

2.5 MHz Bunches by Morphing

To prepare the antiproton beam for injection into the Tevatron, each of the mined antiproton bunches (see Fig. 1(e)) is further subdivided into four smaller bunches defined by a 4-cycle 2.5 MHz sine waveform. The past and present methods adopted to form these bunches are shown schematically in Fig.2. The previous method expanded one bunch and grew a 4-cycle 2.5 MHz sine waveform, resulting in ~30% longitudinal emittance growth. This technique was modified to use waveform morphing (explained earlier), first expanding the beam, growing a 4-cycle 7.5 MHz sine waveform and morphing this waveform to a 4-cycle 2.5 MHz sine waveform. This modification reduced the longitudinal emittance growth to <10%.

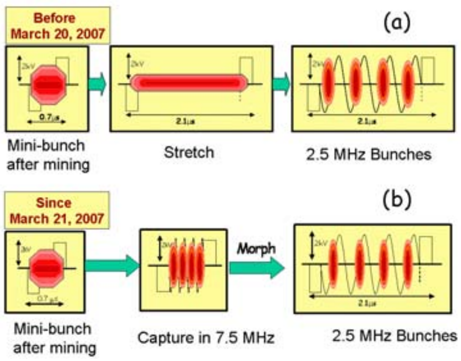

Figure 2: Past and present 2.5 MHz bunch formation techniques. (Past: ~30% longitudinal emittance growth, present: <10% emittance growth).

ACCOMPLISHMENTS AND CURRENT STATUS ON TEVATRON LUMINOSITY

The upgrades described above greatly improved the performance of the LMM and solidified the role of the Recycler in increasing the luminosity performance of the Tevatron complex. Typically we observe less than 5% variation in the mined batch intensity, see Fig. 1e. The final antiproton bunch intensity distribution in the Tevatron at collision is shown in Fig. 3. Bunch-by-bunch luminosity variation was reduced to <15% at collision. Typical emittances for bunches extracted from the Recycler for a Tevatron shot are 2 π mm-mr and 1.0 eV s.

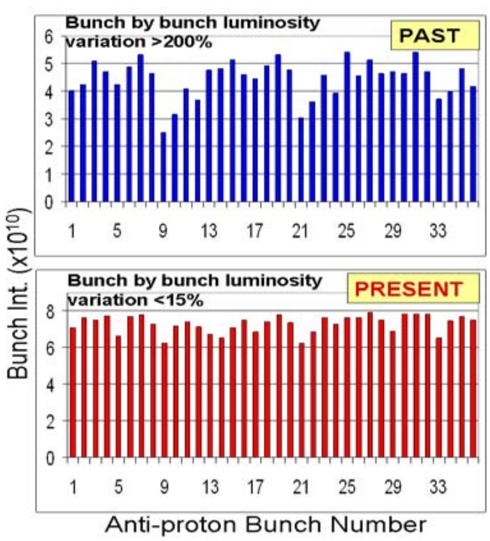

Figure 3: Past and present 53 MHz bunch intensities in the Tevatron at collision. Notice that the bunch intensity variation got reduced significantly in spite of the average intensity went up by 70%.

Figure 4(a) shows peak luminosity variation over the years before and after the LMM was made operational in the Recycler. We have exceeded the Run IIb design goal of 270 μb^{-1} for the peak luminosity. To this point, the Tevatron has delivered ~3 pb^{-1} integrated luminosity to CDF and D0 detectors, with an eventual goal of 8 pb^{-1} to each one of the detectors by the end of the decade.

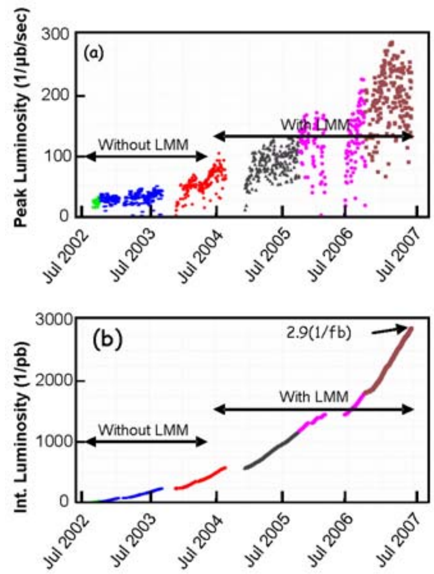

Figure 4: Tevatron luminosity performances before and after the implementation of the longitudinal momentum mining in the Recycler. Different color indicate different fiscal year of operation.

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